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Can SMOS Ocean Salinity data detect a link between increasing Antarctic sea ice extent and freshwater flux from basal melting of Antarctic ice shelves?

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Abstract (337 words):

The drivers behind the observed trend of increasing Antarctic sea ice extent are not yet well understood, though several potential drivers have been identified, such as the increased input of freshwater into the Southern Ocean due to basal melting of ice shelves around Antarctica. Previous studies have found seasonal links between the growth and decay of sea ice and the minimum and maximum input of freshwater from basal melting of ice shelves. A variety of observation and measurement techniques have been used to quantify freshwater input from basal melting, and remote sensing techniques have been recognised as an important opportunity for large-scale monitoring of the surface freshwater balance both in the Southern Ocean and globally. In this study, data products from the European Space Agency's Soil Moisture Ocean Salinity (SMOS) mission are investigated to highlight the strengths and weaknesses of ocean salinity data in detecting salinity and freshwater trends around the Antarctic continent and adjacent to the ice shelves. Several limitations were noted for both data products, including the rejection of data during pre-processing stages due to sea ice presence, land contamination, and too few data measurements. The reliability of data adjacent to the continent and sea ice is therefore substantially reduced, and would benefit from additional investigation into lower-level, unfiltered data that retains the rejected gridpoints, whether this is available through SMOS or a similar mission such as the National Aeronautics and Space Administration (NASA)'s Aquarius mission. However, initial analyses of Level 3 data demonstrated seasonal patterns that correspond with modelled projections of minimum and maximum freshwater input from basal melting of ice shelves, and indicating that there could be a role for remote sensing in monitoring these patterns and, in conjunction with direct measurements, exploring more closely whether freshwater flux from basal melting of ice shelves is a significant driver of increasing seasonal Antarctic sea ice extent. It is vital that biases in SMOS data be addressed, or alternative data sought, to determine the extent to which remote sensing can contribute to this research goal.

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BACKGROUND

Seasonal sea ice in Antarctica interacts with the global climate through its convective, insulating and reflective properties (Hanna, 1996; Lemke et al., 2007). During the seasonal growth of sea ice in the Southern Ocean, brine rejection causes the accumulation of dense, heavy water at the surface of the ocean, which then sinks to the continental shelves to form Antarctic Bottom Water, creating convection that, together with dense bottom water from the Arctic and Greenland, drives global thermohaline circulation (Wadhams, 2000a). This convective activity also carries oxygen and dissolved CO_2 into deeper waters, permitting life to flourish in the deep ocean (Wadhams, 2000a). Areal coverage of sea ice regulates the exchange of heat, momentum and gases (such as water vapour and CO_2) between the atmosphere and ocean, acting as an insulating layer to prevent heat from the ocean escaping into the atmosphere (Dieckmann & Hellmer, 2003; Lemke et al., 2007). It also plays a significant role in the 'ice-albedo' feedback, a positive feedback mechanism in the climate where decreasing sea ice (and snowline) extent decreases surface albedo, permitting higher amounts of solar radiation to be absorbed at the surface, which then becomes warmer (Eicken, 2003; Wadhams, 2000b). This cycle acts as an amplification of warming, further reducing the extent of ice and snow, as has been observed in the Arctic (Pistone et al., 2014). Seasonal sea ice also plays an important role in sustaining marine ecosystems, and provides habitats for Antarctic species ranging from microorganisms (Lizotte, 2003; Schnack-Schiel, 2003) to birds and mammals (Ainley et al., 2003).

The importance of sea ice to the global climate system has compelled substantial research into characteristics such as concentration, thickness, extent, area, velocity, and rates of growth and decay (Lemke et al., 2007). Sea ice in the Southern Ocean differs significantly from that of the Arctic; for example, a majority of Antarctic sea ice is first-year ice, and therefore much thinner than the large proportion of Arctic multi-year sea ice, and Antarctic sea ice also has higher salinity and a significantly higher drift velocity (Dieckmann & Hellmer, 2003). These properties can reduce the capability of some remote sensing techniques to observe sea ice in the Southern Ocean, and the lack of long-term continuous data in the Antarctic region is a barrier to producing assessments of decadal and longer-term trends and changes to Antarctic sea ice prior to the satellite era (Vaughan et al., 2013).

Satellite imaging of the Southern Ocean and Antarctica commenced in the early 1970s, with continuous sea ice extent data available from 1979 (Lemke et al., 2007). In a recent study, discrete data of sea ice extent for September 1964 and May-July 1966 were also added to the long-term dataset to extent the observational record to 50 years, instead of the continuous dataset of 35 years (Gagné et al., 2015). Studies utilising both the 1979-2014 and 1964-2014 datasets have identified a small increasing trend overall in Antarctic sea ice extent, as well as some substantial regional trends (Gagné et al., 2015; Parkinson, 2014; Parkinson & Cavalieri, 2012; Vaughan et al., 2013). One particular study by Parkinson and Cavalieri (2012) divided the ocean surrounding Antarctica into five sectors and analysed trends in sea ice extent in each sector from satellite imagery between 1979 and 2010, as shown in Table 1.

Table 1: Average annual sea ice extent trends for the five Southern Ocean sectors surrounding the Antarctic continent (Parkinson & Cavalieri, 2012)

Sector	Annual Trend ($10^3 km^2 yr^{-1}$)	% per decade
Ross Sea	+ 13.7 ± 3.6	+ 5.2 ± 1.4
Weddell Sea	+ 5.2 ± 4.5	+ 1.2 ± 1.1
Amundsen/ Bellingshausen Seas	– 7.8 ± 2.5	– 5.1 ± 1.6
Indian Ocean	+ 5.8 ± 2.2	+ 3.2 ± 1.2
Western Pacific Ocean	+ 0.6 ± 1.8	+ 0.5 ± 1.5

As can be seen in Table 1, the trend of largest magnitude is the positive trend in the Ross Sea region, with approximately 5.2% increase in extent per decade. The second largest magnitude is that of the Amundsen/Bellingshausen Seas, a negative trend of approximately –5.1% per decade. Regional trends in sea ice extent in the oceans surrounding Antarctica are strongest around the edge of the ice, alternating in positive and negative trends around the continent (Vaughan et al., 2013). For the Southern Ocean overall, the annual trend has been calculated as a statistically small increase of approximately 1.3-1.8% per decade between 1979 and 2012 (Vaughan et al., 2013). There is high confidence in the overall increasing trend of sea ice extent in Antarctica, as well as in the strong regional differences that have been identified (Parkinson, 2014; Parkinson & Cavalieri, 2012; Vaughan et al., 2013).

Currently, global coupled climate models in the 5th phase of the Coupled Model Intercomparison Project (CMIP5) do not replicate the observed overall increase in sea ice extent in Antarctica; instead, most models simulate an overall decrease in sea ice extent, similar to that observed in the Arctic but at a slower rate (Turner et al., 2013). Some models have simulated an increase in Antarctic sea ice extent, but these results only appear in a small number of ensemble runs and generally overestimate observed trends (Turner et al., 2013; Uotila et al., 2013). There has been substantial investigation in recent years into the drivers and causes of Antarctic sea ice trends, but as yet, no scientific consensus exists to explain the disparity between the observed increase in sea ice extent and the failure of climate models to accurately reproduce these trends. The Intergovernmental Panel on Climate Change (IPCC) thus states that there is *low confidence* in both current scientific understanding of the drivers of change to sea ice extent, and in model replication of observed sea ice extent in Antarctica (Bindoff et al., 2013).

Research into the drivers or change to sea ice in the Southern Ocean has revealed several theories. Early investigations proposed that the influence of stratospheric ozone depletion on oceanic and atmospheric conditions could be driving increases in sea ice extent (Turner et al., 2009); however, more recent studies have demonstrated that ozone depletion is associated with decreases in sea ice extent (Bitz & Polvani, 2012; Sigmond & Fyfe, 2010,2014). It has also been suggested that changes atmospheric circulation over the Antarctic region (Holland & Kwok, 2012) and/or an increase in the index of the Southern Annular Mode (SAM) could be strong influences (Goosse et al., 2009; Sen Gupta & England, 2006; Stammerjohn et al., 2008). Freshening of surface waters in the Southern Ocean due to amplified calving and basal melting of ice shelves has been suggested as a driver of increased ocean stratification, permitting surface waters to freeze at higher temperatures than is possible in more saline water, which could result in increasing sea ice extent (Bintanja et al., 2013). As stated previously, none of these theories are considered to be conclusive at present, and the significant uncertainty surrounding the dynamics and interactions of the suggested drivers warrants additional research and model replication of these potential drivers before the increased ice extent can be attributed to any (or a combination) of the drivers with a high level of certainty (Bindoff et al., 2013).

This paper focuses on freshwater flux from basal melting as a potential driver of sea ice extent, highlighting the apparent seasonal link between basal melting of ice shelves and seasonal sea ice extent in Antarctica, and the oceanic circulation patterns that connect them. After a brief overview of the dynamics and interactions of basal melting and sea ice extent, observation methods of sea surface salinity will be discussed followed by an investigation into the potential for remote sensing techniques to observe changes to surface salinity levels around Antarctica, and whether this data can be used to determine a link between trends in sea ice extent and freshwater flux from melting ice shelves.

BASAL MELTING OF ICE SHELVES

Mass balance of ice shelves is the difference between the rate of accumulation and the rate of ablation. Ice shelves gain mass through precipitation, being fed by glaciers, and by freezing on the underside of the floating ice; they lose mass through calving of icebergs, basal melting, and topside processes such as sublimation and wind-driven snow drift (Rignot et al., 2013). Calving has conventionally been considered the method through which ice shelves lose the largest proportion of their mass, but more recent analysis has shown that in fact basal melting is the most substantial ablation process for Antarctic ice shelves, accounting for approximately half the net loss of ice (Depoorter et al., 2013; Rignot et al., 2013). Rapid thinning of ice shelves around Antarctica has been observed since the beginning of the 21st century (Rignot et al., 2013), and is predicted to have a strongly regional response under future oceanic and atmospheric warming (Kusahara & Hasumi, 2013). There are three modes through which basal melting occurs, each related to ocean circulation (Figure 1).

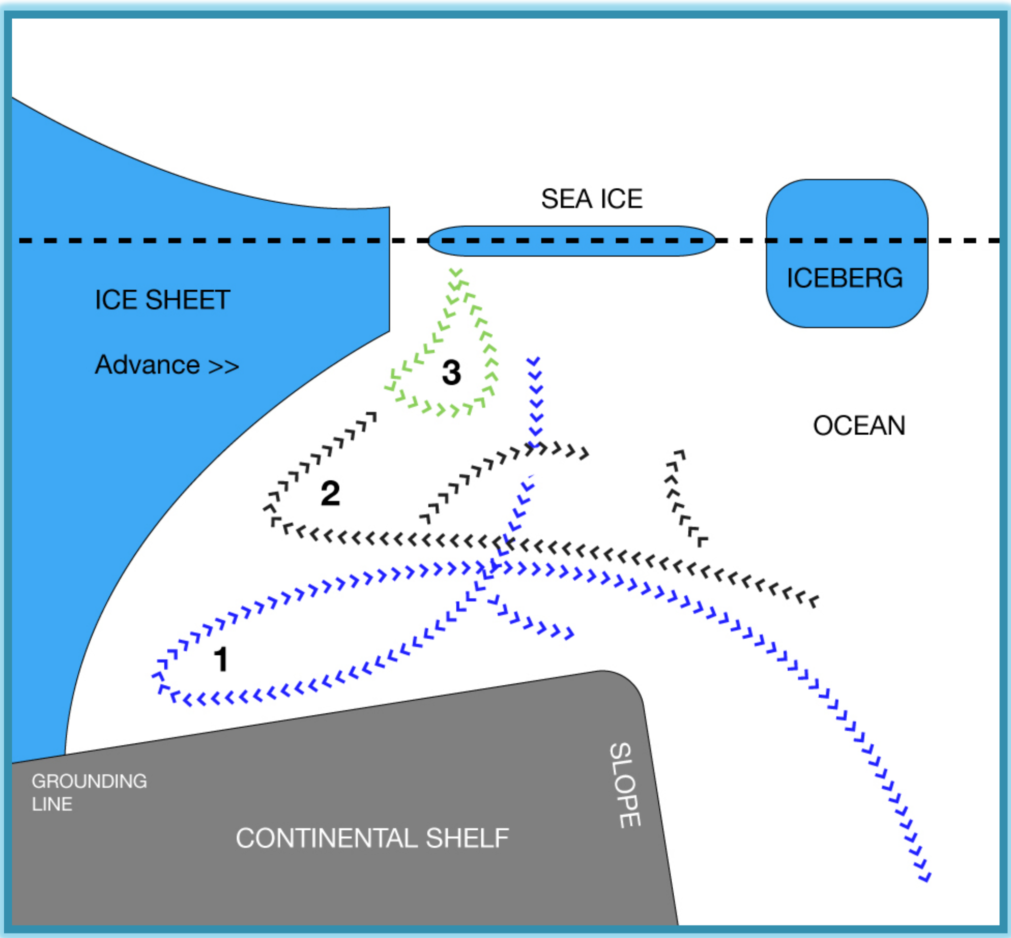

Figure 1: Three modes of basal melting of Antarctic ice shelves (adapted from Jacobs et al. 1992)

In the first mode, high-salinity shelf water (HSSW), caused by brine rejection from sea ice growth in winter, sinks beneath the ice shelves towards the grounding line, it cools below the surface freezing temperature due to the decrease in freezing temperature under increased salinity and pressure (Holland et al., 2003). Latent heat is released through melting of the ice shelf and is conducted into the ice, after which freezing occurs and commences the evolution of very cold but relatively fresh Ice Shelf Water (ISW) (Depoorter et al., 2013; Jacobs et al., 1992). The second mode is the intrusion into the basal cavity of circumpolar deep water, which has a temperature significantly warmer than the freezing temperature at the surface (Depoorter et al., 2013; Jacobs et al., 1992). In the third mode, large basal loss rates are caused by the mixing of fresh, warm surface water at the edge of the ice shelf, driven by wind and tidal fluctuations (Depoorter et al., 2013; Jacobs et al., 1992; Zhou et al., 2014). Ice shelf processes, and temperature-dependent basal melt are not yet adequately incorporated into current global coupled climate models (Bintanja et al., 2013; Kusahara & Hasumi, 2013), and where they have been incorporated into sea ice-ocean coupled models, results illustrate strong regional variation in heat sources and in basal melting response (Kusahara & Hasumi, 2013).

LINKS BETWEEN BASAL MELTING AND SEA ICE

Basal melting is strongly influenced by seasonality and has been linked with formation and decay of seasonal Antarctic sea ice, with modelling of the Ross Ice Shelf by Holland et al. (2003) presenting a peak net melt rate at the end of winter, linked to the winter inflow of High Salinity Shelf Water (HSSW) from the growth of sea ice at the surface. Similarly, Assman et al. (2003) found a bimodal seasonal cycle for basal melting of the Ross Ice Shelf with maxima in August, due to high convective activity from winter sea ice growth causing strong sub-surface circulation, and also in March, due to the intensified circulation of warm summer surface waters into the basal cavity. Between December and early January, thermal stratification of the waters beneath the ice shelf occurs, increasing levels of salinity; this is reversed to the winter ‘cold state’ by early May to late July (Arzeno et al., 2014). This corresponds with the bimodal minima also found by Assman et al. (2003) in May and December; the May minimum is due to cool waters and low circulation strength, and in December, water temperatures near the ice shelf are too cold for melting to occur, and freezing takes over. Model simulations show that freshwater input from basal melting freshens and cools continental shelf water supplied by warm and saline ocean currents, leading to increased stratification of the water column around the ice shelf that is carried along by strong oceanic circulation patterns (Hellmer, 2004). Stronger stratification of the water column also reduces the convective momentum of sea ice formation and decay, which reduces the transfer of heat to the surface, causing thickening of sea ice (Hellmer, 2004) and increased sea ice extent (Bintanja et al., 2013). Clearly, there are complex interactions between the formation and decay of sea ice, ocean circulation, and melting at the base of the ice shelves that are not yet fully understood, but may be contributing to a positive feedback in the climate where warmer surface temperatures may increase basal melting through intensified ocean convection, thereby strengthening stratification which weakens oceanic convection and produces thicker and more extensive sea ice.

OBSERVING BASAL MELTING

The difficulty of accessing basal cavities of ice shelves has made it difficult to measure melting rates directly. Several data-retrieval methods have been attempted and have evolved over time to more closely monitor the interactions of the ocean and ice shelf, and to examine potential effects of global and regional climate trends in the future (Kobs et al., 2014). For example, conductivity-temperature-depth measurements have been taken at the ice-shelf front, and direct measurements have also been taken, though infrequently, by drilling down through the ice shelf itself (Catania et al., 2010). Studies have undertaken the use of autonomous underwater vehicles to take physical measurements and to study the topographic and oceanographic environment (Nicholls et al., 2006). Phase-sensitive radar has been utilised to detect changes in thickness between the grounding line of the ice shelf and an ‘upper reference horizon’, though these measurements are likely to be biased through surface compaction, and the lack of an internal reference point reduces its precision (Corr et al., 2002). Estimation can be made of ice shelf flux through calculations of thickness, velocity and accumulation under a steady-state assumption, which has previously suffered from sparse thickness data (Catania et al., 2010); however, in recent years there have been substantial improvements in data for these parameters, enhancing the accuracy of estimations (Lemke et al., 2007). Catania et al. (2010) use remote observations through ice-penetrating radar to measure the characteristics of sub-ice-shelf and basal melting. More recently the installation of fibre-optic cable moorings in the McMurdo Ice Shelf and its basal cavity permitted observation of changes to the thermal gradient of the ice shelf waters at a high spatial resolution (Kobs et al., 2014).

These experiments have significantly expanded upon the state of knowledge of ice-ocean dynamics at the base of the ice shelf as well as the topography of ice shelf through a variety of temporal and spatial scales; however, continuous, long-term monitoring of changes in the water column and basal mass loss from ice shelves has not yet been established (Catania et al., 2010; Kobs et al., 2014).

REMOTE SENSING OF SEA SURFACE SALINITY

Initial attempts to map sea surface salinity (SSS) from space began with the SKYLAB satellite, in operation during 1973-74, which used intermittent passive microwave radiometer measurements to determine if SSS measurements could be captured from instruments orbiting in space (Lagerloef et al., 1995; Lerner & Hollinger, 1977). Their encouraging results spurred the progress of airborne salinity measurements through the 1980s, and demand for further development for satellite remote sensing technology in the 1990s (Lagerloef et al., 1995). A Salinity Sea Ice Working Group (SSIWG) was established in 1998, with the goal of assessing and evaluating the importance of higher spatial and temporal observations, and the potential for satellite measurements of SSS from space given technological advances during the previous decade and likely developments in the future (Lagerloef et al., 2008). The SSIWG coordinated and assisted the study of satellite sensor designs, and later the launch of two explorer-class missions. In November 2009, the European Space Agency (ESA) launched the Soil Moisture Ocean Salinity (SMOS) mission, utilizing the Microwave Imaging Radiometer using Aperture Synthesis (MIRAS), an L-band radiometer that operates at 1.4GHz (European Space Agency, 2015). It is expected to continue operation until 2017 (European Space Agency, 2015). Soon after, in August 2011, the Aquarius/SAC-D mission, coordinated by the USA National Aeronautics and Space Administration (NASA) and the Argentinian National Space Activities Commission (CONAE), was launched (NASA, 2015a). It combines three of the most highly sensitive radiometers of the time, to detect ocean salinity, and a scatterometer, to correct for surface roughness, in an active and passive L-band (1.4GHz) microwave instrument (Le Vine et al., 2010). The baseline for the mission is 3 years, but could last up to 12 years or more (NASA, 2015b).

The L-band is a low-frequency band, as although microwave emission from the ocean is highly dependent on temperature and salinity, at low frequencies, emissions are more dependent on salinity levels than on temperature (Blume et al., 1978). The low frequency band at 1.4 GHz has sufficient sensitivity to salinity to capture the polarised brightness temperature of the ocean surface based on the *dielectric constant* of seawater, which is determined by its salinity and temperature in the top one centimetre of the surface water (Blume et al., 1978; Font et al., 2010). This band is also legally reserved for the purposes of science (i.e. remote sensing and radio astronomy) to prevent interference from radio signals (Font et al., 2010; Lagerloef et al., 2008). However, in order to accurately measure surface emission, corrections are required for atmospheric radiation and transmission, and also for the roughness of the ocean surface (Blume et al., 1978). Models for the dielectric constant and corrections have been much improved in recent years, but research continues to further update these parameters (Lagerloef et al., 2008).

Though the SMOS and Aquarius missions are intended to share the objective of mapping sea surface salinity, the output of the sensors varies significantly due to differences in modelling, calibration and correction (Dinnat et al., 2014). For example, a different dielectric constant model is used in each mission, which results in significant variation in high-latitude waters between the two datasets. Research is ongoing to address algorithm inconsistencies in the two missions and to analyse new techniques for improving SSS data retrieval (Dinnat et al., 2014). Furthermore, the two missions have different swath coverage, spatial resolution, and revisit times (3 days for SMOS; 7 days for Aquarius) (Pablos et al., 2014). These differences make direct comparison between the two datasets challenging, and is an area of increased scrutiny in order to create a continuous, homogenised dataset for long-term observation, such as an environmental or climatological study (Pablos et al., 2014).

Remote sensing is an efficient method of observing large-scale and chiefly inaccessible regions, such as the surface waters surrounding the ice shelves of Antarctica. However, it is not without fault; for example, obtaining remotely sensed salinity data in high latitude waters is hindered by the lower strength of the radiometric signature at colder ocean surface temperatures (Lagerloef et al., 2008). In the case of the Aquarius mission, however, the curvature of the Earth causes swath overlap in high-latitude regions, resulting in higher sample density that can be averaged across several samples, albeit with higher error allocation than lower latitudes (Lagerloef et al., 2008). Furthermore, only salinity of the top centimetre of water is detected, not the entire water column adjacent to the ice shelf (Font et al., 2010). Nevertheless, remote sensing techniques have been utilised in conjunction with direct measurements and modelling capability to detect rates of calving flux and basal melt in ice shelves around Antarctica, to measure Antarctic-wide freshwater flux, and to study regional trends in freshwater melt rates (Bindschadler et al., 2011; Depoorter et al., 2013; Trusel et al., 2012; Trusel et al., 2013). The SSIWG have acknowledged that the combination of satellite and underwater measurements are needed to create a global monitoring system for interannual and decadal trends in regional and global ocean surface salinity (Lagerloef et al., 2008).

The SMOS mission seeks to contribute to many large-scale climatological and meteorological research goals, one of which is observation of the surface freshwater flux balance (Font et al., 2010). Here, it is investigated whether sea surface salinity data from the SMOS mission can detect surface freshwater flux from basal melting around Antarctica, and whether the data it collects can be compared with sea ice extent trends to measure potential links between these two components of the ice-ocean interface.

METHODS AND RESULTS

Sea surface salinity (SSS) data was obtained from the ESA SMOS mission for the Southern Ocean (for latitudes south of 60° S). Level 3 Ocean Salinity (OS) data was considered initially, and minimum, maximum and average salinity inferred from data over the period from January 2014 – December 2014. Capability and weaknesses in salinity measurements adjacent to sea ice and ice shelves were noted.

Subsequently, Level 2 OS data was analysed, to investigate its capability for measuring salinity over Level 3 data. The results and limitations of both data products are discussed in more detail in the following section.

LEVEL 3 OS DATA

The ESA Level 2 OS data is obtained from the SMOS Online Archive via FTP, for which access is granted directly from ESA. Firstly, an Earth Online Single Sign-On (EO-SSO) account must be activated, after which Principal Investigator (PI) registration is granted. This enables access to the SMOS Barcelona Expert Centre (SMOS-BEC) online repository, from which Near Real Time Level 3 products can be directly downloaded upon demand. These products encompass Binned global maps and Optimally Interpolated global maps, each of which is available in several temporal scales (described further in Table 2).

Table 2: SMOS OS Level 3 Products

Level 3 Product Type	Description	Temporal scales
Binned	Created using a weighted averaging across the values of the filtered Level 2 grid at a resolution of 1° by 1°	3-day average 9-day average Monthly Seasonally Annually
Optimally Interpolated	Created using 0.25° x 0.25° grid binned Level 2 data, producing grids with fewer gaps and higher levels of data consistency than the alternative Binned Level 3 product	9-day average Monthly Seasonally Annually

Level 3 data products are computed using the Level 2 User Data Products (UDP) and Ocean Salinity Data Analysis Product generated by ESA. In order to reduce noise in salinity measurements, Level 2 data undergoes geophysical, retrieval, and geometric filtering prior to use in producing any Level 3 product (SMOS-BEC, 2013). The geophysical filtering includes the rejection of salinity data in gridpoints where the presence of ice is suspected (i.e. >50% of measurements return a positive ice score). It has been acknowledged that minimal information on sea ice characteristics will be obtained from SMOS data measured over the sea ice compared with other satellite observations and instruments (Mills & Heygster, 2011). Similarly, gridpoints collected from near the coast are considered 'contaminated' due to the presence of land, and are filtered out during pre-Level 3 processing (Font et al., 2013). This results in large biases in data collected close to land and ice (Boutin et al., 2012), presenting a problem for accurate observation of seasonal salinity and freshwater flux in surface waters around the ice shelves of the Antarctic continent.

The resolution of the Level 3 SMOS OS data is very coarse; while the salinity data from the SMOS instrumentation was captured at ~40km spatial resolution (Pablos et al., 2014), it was then reprocessed by the European Space Agency to a resolution of *1 pixel = ¼ ° latitude and longitude,* in order to reduce the computational cost of interpolation for missing data, where the sensor was not able to collect information (CP34-BEC, 2015). This results in a lower spatial resolution overall. Furthermore, because the Optimally Interpolated data obtained from ESA were 9-day, monthly, seasonal or annual averages, the data was further reduced in resolution by the carrying forward the data losses during the averaged period, limiting detailed inferences from the dataset. The example in Figure 2 below is a 9-day SSS average image from the Optimally Interpolated Level 3 product encompassing February 1, 2014 (chosen for proximity to the sea ice extent minimum).

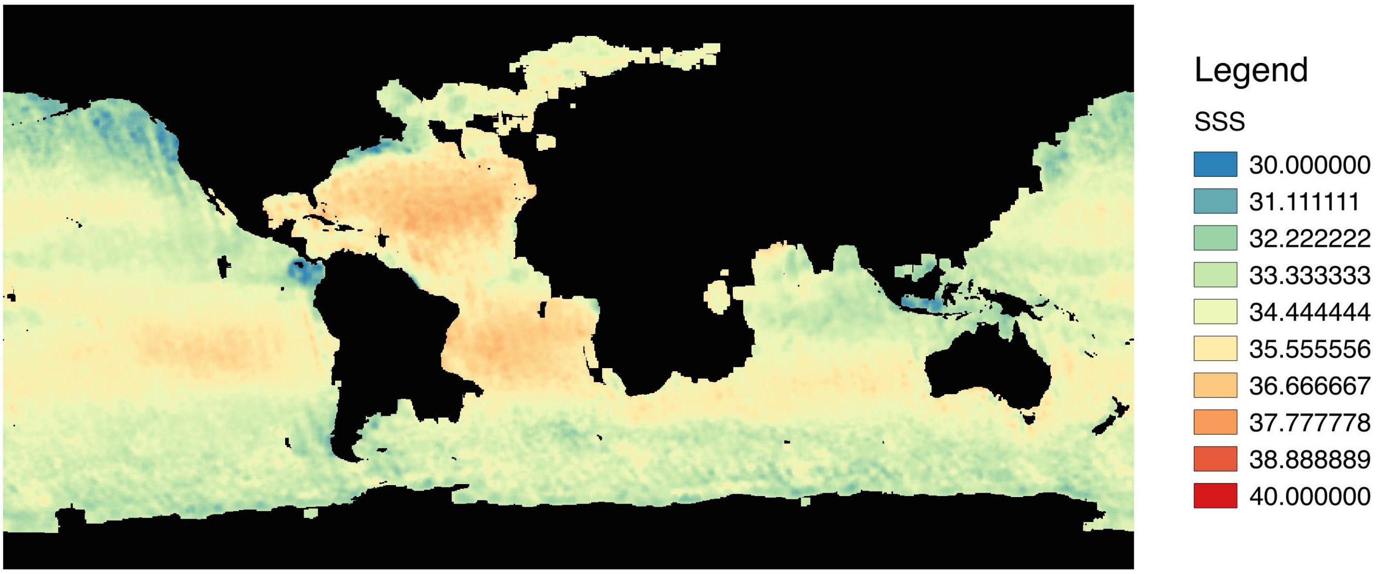

Figure 2: Level 3 Optimally Interpolated global map of SSS (in psu) for a 9-day average encompassing February 1, 2014

In Figure 3, a stereographic image (in which the projection is centred over the South Pole to reduce grid distortion over Antarctica) illustrates the monthly-averaged Optimally Interpolated Level 3 product for February 2014, during which time the sea ice reaches its minimum extent and salinity should, due to minimum brine rejection during sea ice formation, be at its minimum at the ocean surface.

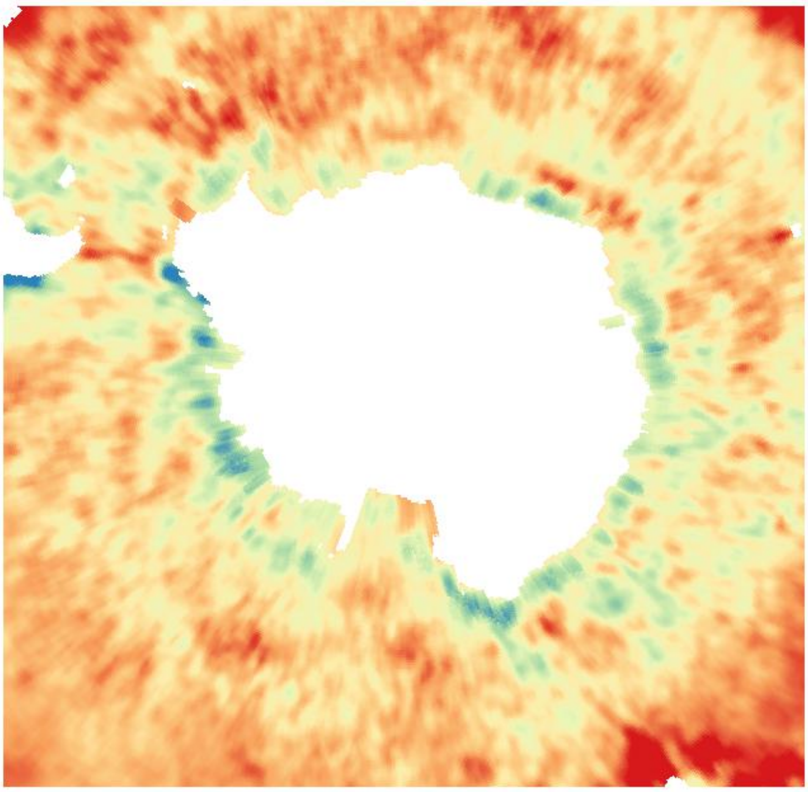

Figure 3: Polar stereographic image of SMOS Level 3 Optimally Interpolated SSS monthly data product for February, 2014 (see Figure 4 for detailed legend)

The SMOS sensors are able to detect increasing salinity moving further away from the Antarctic continent, with regional patterns and variations around the continent as well. It is clear in this image that, generally, the lowest values surrounding Antarctica occur adjacent to the continent, where freshwater flux is high during this month. However, as discussed previously, there is a significant amount of information likely to be lost through averaging to create an optimally interpolated image, and this image encompasses a period where sea ice extent is changing significantly (reaching minimum extent during the month and then beginning to grow again), which are substantial processes masked by the creation of a monthly average.

Figure 4 shows monthly polar stereographic images encompassing January 2014 to December 2014. This image excludes the months of October and November, for which ESA data was not generated due to a SMOS instrument anomaly that prevented accurate retrieval of Level 2 OS data (CP34-BEC, 2015). For a larger, more detailed version of Figure 4, please see Supplementary Information.

At a glance, there appears to be a bimodal distribution of SSS in the Southern Ocean, with salinity peaking in December and May, and reaching minimum values in March and August. To investigate this further, the global data was subset into a domain, or study area, and the raster clipped (using a built-in convex hull operation to create the minimum-enclosing polygon) to the coordinates listed in Table 3.

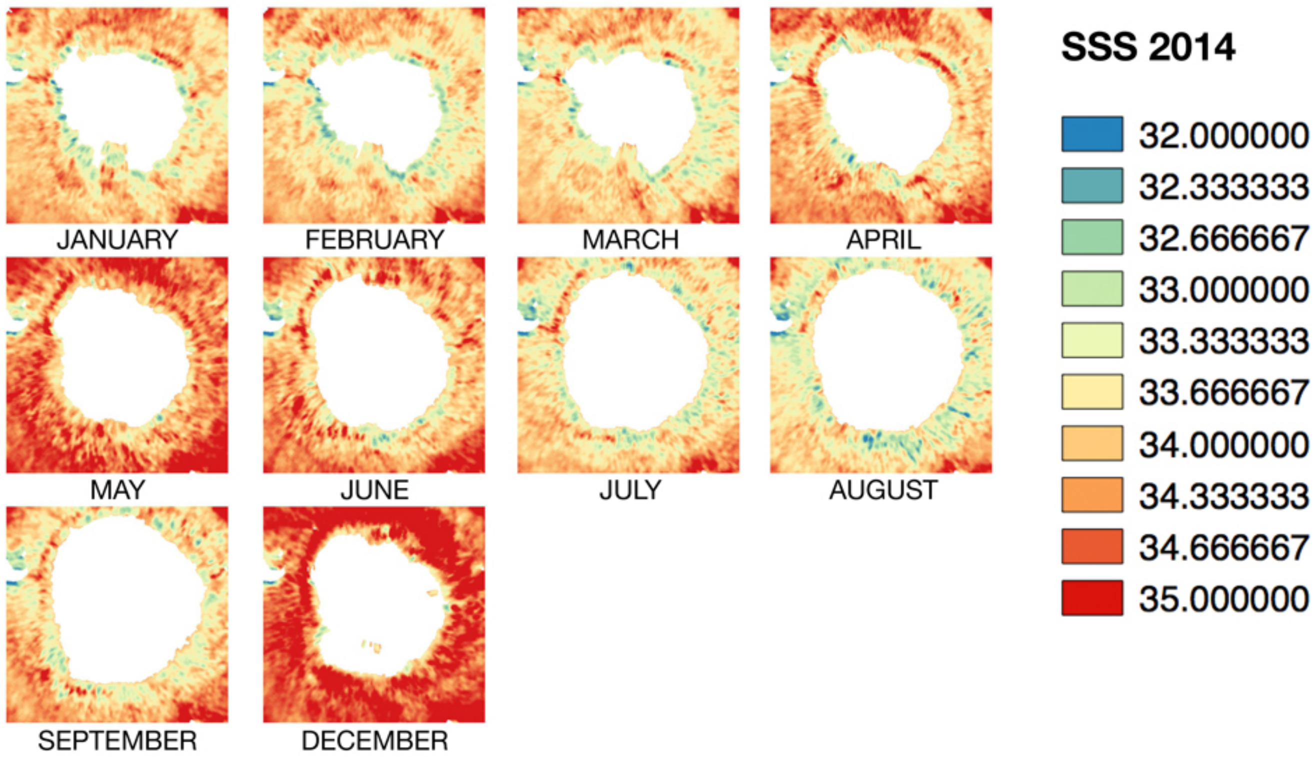

Figure 4: Polar stereographic images of SMOS Level 3 Optimally Interpolated SSS monthly data product (in psu) from January 2014 - December 2014 (excluding October 2014 and November 2014 due to instrumentation error)

Table 3: Longitude and latitude coordinates of the study area in the Southern Ocean

Point	Longitude	Latitude
Upper Left	180° W	60° S
Upper Right	180° E	60° S
Lower Left	180° W	90° S
Lower Right	180° E	90° S

The clipped rasters were then read into Python using GDAL (Geographic Data Abstraction Library), from which statistics could be computed and graphed using MATPLOTLIB (a Python graphing package). The statistics of interest were minimum, maximum and average SSS, and are shown below in Figures 5 – 7. Although the charts show linear progression between September and December, due to the missing data in October and November, caution is warranted when inferring trends of salinity between September – December as the graph is not necessarily representative of true observations over this period.

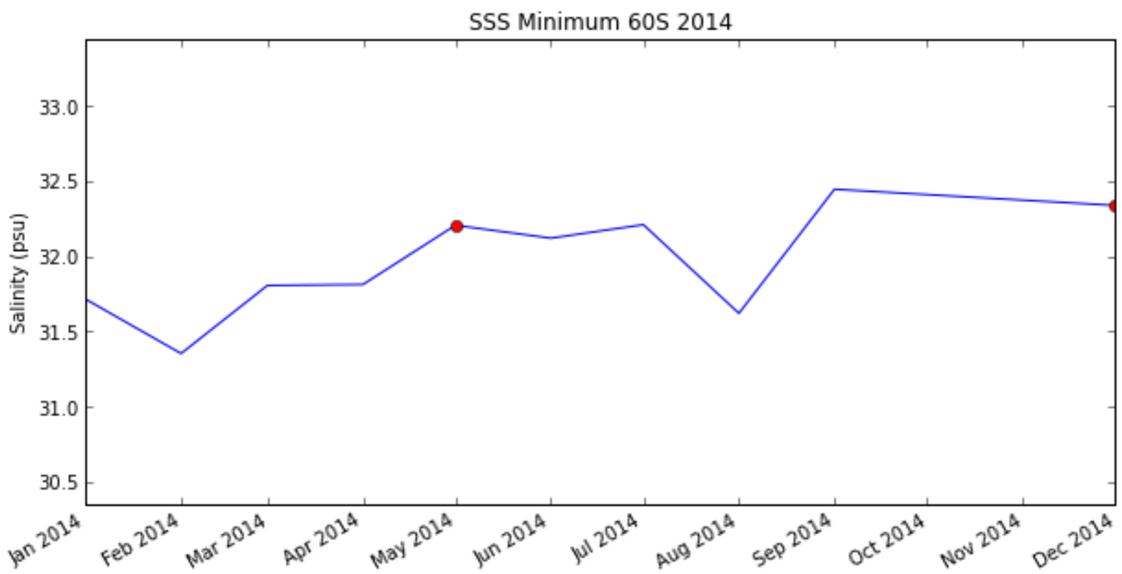

Figure 5: Minimum monthly SSS from SMOS Level 3 Optimally Interpolated SSS data product from January 2014 - December 2014 (excluding October and November due to instrumental error)

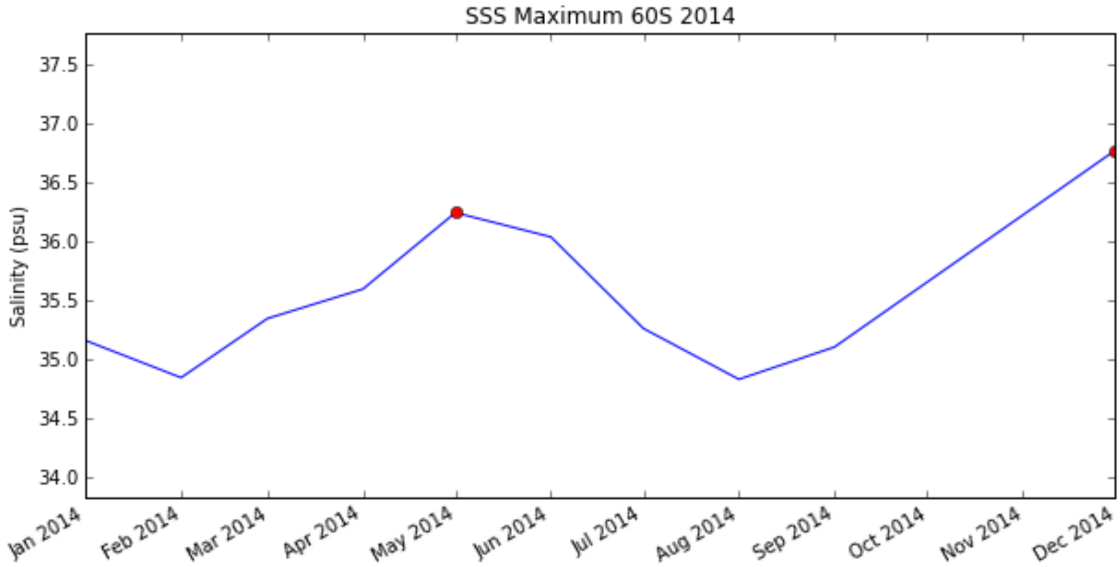

Figure 6: Maximum monthly SSS from SMOS Level 3 Optimally Interpolated SSS data product from January 2014 - December 2014 (excluding October and November due to instrumentation error)

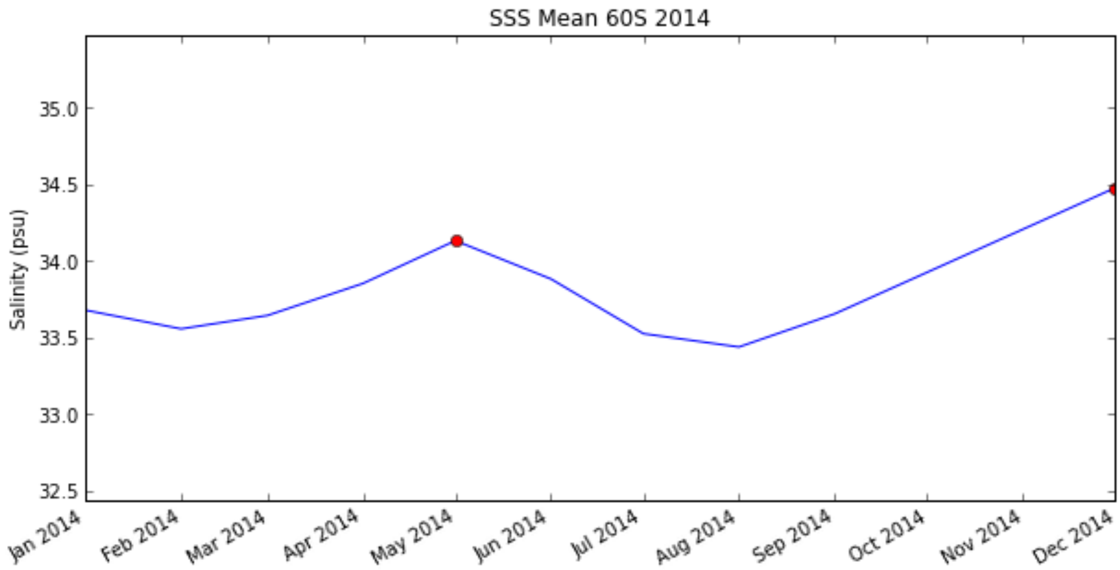

Figure 7: Average monthly SSS from SMOS Level 3 Optimally Interpolated SSS data product from January 2014 - December 2014 (excluding October and November due to instrumentation error)

Figures 5 – 7 clearly demonstrate the presence of a bimodal distribution in salinity during the course of the year, with maximum values occurring in May and December and minimum values occurring in August and February. These findings are considered further in the Discussion section of this paper.

LEVEL 2 OS DATA

Due to the coarse resolution of Level 3 data discussed above, resulting from data loss (through averaging) and rejection of data due to sea ice presence, land contamination, and infrequency of measurements, significant limitations were placed upon how much detail could be inferred from the resulting imagery. To determine any existing difference in quality of sea-ice and continent-adjacent measurements of salinity between Level 3 and Level 2 OS products, the study also analysed Level 2 OS data of an individual half-orbit swath taken on February 1, 2014.

To obtain Level 2 OS data, confirmation of interest was required by ESA, necessitating a double opt-in for access to a restricted set of data via FTP. The files were arranged in year-month-day folders, with up to 30 individual half-orbit swath-based map files representing a single day. Files were in DBL format with a header file (HDR; an xml schema describing the data). This was opened using the VISAT application, a proprietary software package that, with the addition of a number of ESA-supplied plug-ins, is capable of reading and analysing SMOS data. This data was exported in Figure 3 and 4 below.

Level 2 data also undergoes rejection of data due to ice presence and missing data (ARGANS, 2009). In the HDR file for Figures 3 and 4, it was noted that from a total size of 134,250,498 pixels (16,386 width; 8,193 height), 6264 pixels were rejected due to ice presence and 22570 pixels were rejected due to too few measurements having been taken. This suggests that, in order to preserve the integrity of measurements taken close to sea ice or the continental edge, acquisition and investigation of lower-level, unfiltered data from SMOS would be desirable; however, this level of data (and whether it is indeed available at all) was not considered in this study, and would be an ideal area for future research.

These images demonstrate the higher resolution of swath-based data; however, the individual swath files still require stitching and interpolation to obtain a high-resolution global map. The current instructions and software (VISAT) obtained from ESA are insufficient to reproject the data to polar stereographic at present; however, ESA does supply a command-line conversion tool to convert data from proprietary DBL (datablock) format to NetCDF format, which is a common format that can be processed by a number of non-proprietary software packages. This conversion was outside of the scope of this study, and is another area where future study would be of interest to create global maps of SSS that can more accurately reflect values close to sea ice and the edge of the Antarctic continent.

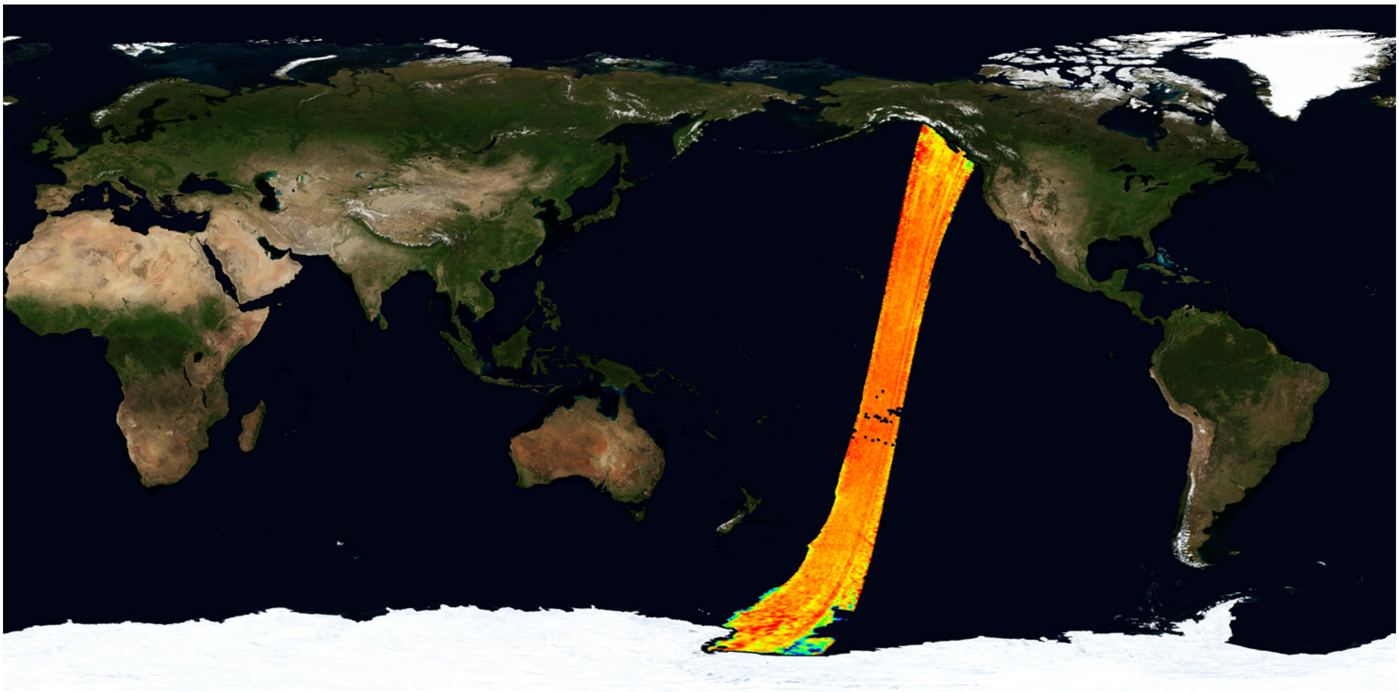

Figure 8: Half-orbit swath-based SMOS Level 2 data product from February 1, 2014

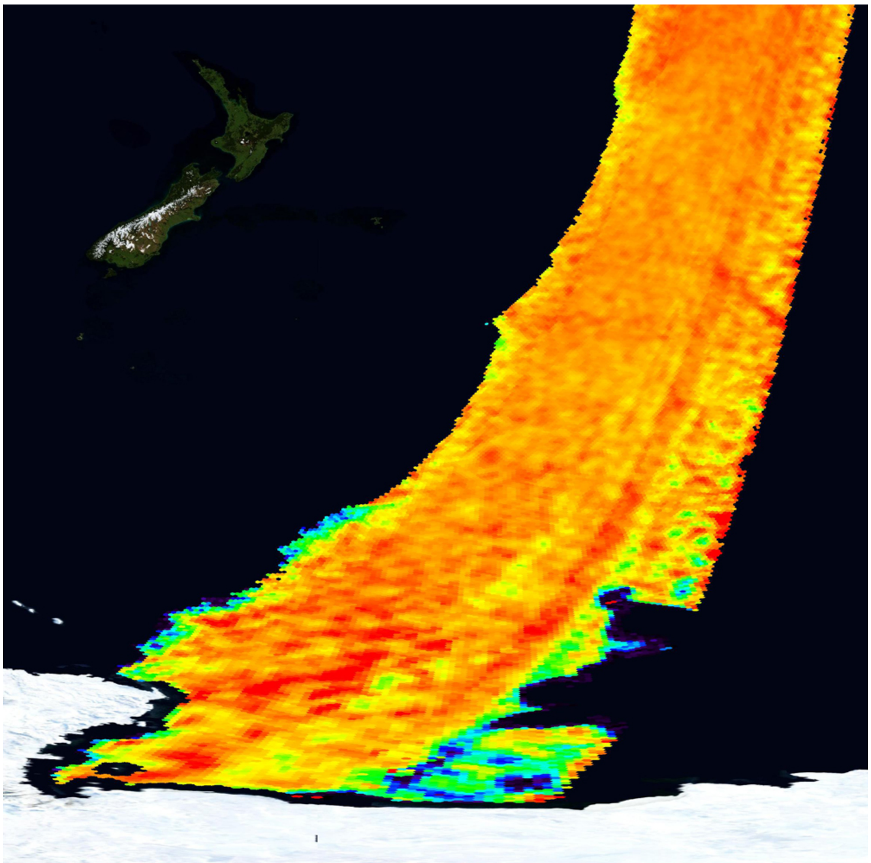

Figure 9: Close-up view of the Ross Sea region from Figure 8

DISCUSSION

The changes in salinity in the Southern Ocean as shown in the monthly-averaged data of Figure 4 indicate a bimodal minima and maxima of salinity over the course of the year. It should be noted that, as a variable with the capability to change on a very short timeframe due to sea ice growth or decay, short-term variations in freshwater flux and salinity could easily be masked by the data loss incurred during monthly averaging. Furthermore, as a single year of observation, this study is merely an example of the capability of SMOS ocean salinity data in the Antarctic region, and does not constitute a thorough examination of annual or seasonal trends in SSS of the Southern Ocean.

However, the monthly-averaged data in Figures 5 – 7 do provide an indication that surface freshwater fluctuations are in agreement with seasonal cycles found in previous studies (Assmann et al., 2003; Holland et al., 2003). The minimum value for salinity in the top 1cm of ocean around Antarctica (i.e. the time of year when the water is the most fresh) is shown to occur in August, with a second (smaller) dip in salinity in February (Figure 6). Antarctic sea ice reaches its minimum extent in February, and its maximum extent in September (Vaughan et al., 2013). As discussed earlier in this paper, Assman et al. (2003) found that freshwater flux reached its maximum in August, due to the growth of winter sea ice causing increased convection causing basal melting, and also in March, from ocean circulation causing warm surface waters to reach the basal cavity. Modelling by Holland et al. (2003) also showed maximum basal melt rates (and hence, high levels of freshness) towards the end of winter. The SSS Level 3 Optimally Interpolated data for 2014 reflects these seasonal patterns, and though due to the many limitations of Level 3 data discussed in this paper, it is too early to say that this is a definitive link, these results do suggest that remote sensing could be a useful complement to direct measurements in detecting seasonal trends and variations in freshwater flux over a longer term.

Future research should focus on reducing the documented SMOS data biases from land contamination and sea ice presence (Boutin et al., 2012), which is currently a barrier to accurate remote sensing of seasonal salinity and freshwater flux in Antarctic surface waters. This is an area that will benefit from, and is currently undergoing, further research (Font et al., 2013). It is also important for future studies to consider whether other data of a similar type is experiencing the same weaknesses (e.g. the Aquarius mission). Obtaining low-level data of both SMOS and other missions to prevent rejection of sea ice presence would be a useful place to commence in order for researchers to perform more in-depth analyses of these gridpoints and consider whether they in fact require separate processing to obtain accurate ice-adjacent salinity information.

CONCLUSIONS

The observed increasing trend of seasonal sea ice extent in Antarctica is an area of high importance and relatively low understanding in current climate science, and drivers such as freshwater flux from basal melting of ice shelves are under investigation to consider their role in increasing sea ice extent in the Southern Ocean. One of the objectives of the SMOS mission is to use remotely sensed data to aid large-scale climate science and meteorological studies, such as global surface freshwater balance. This study explores whether SMOS Level 2 and Level 3 data can be used to contribute to mapping Southern Ocean circulation patterns and dynamics between freshwater flux and the growth and decay of seasonal sea ice.

A number of limitations were found in the samples of SMOS data that were utilised. Firstly, measurements from the SMOS mission are limited to the brightness temperature in the top centimetre of water, whereas freshwater flux and sea ice dynamics occur throughout the entire water column. This necessitates the use of remote sensing as a complementary measure, rather than a tool in its own right, for freshwater and salinity detection. The need to use remote sensing as in conjunction with direct measurements to create a global monitoring system for ocean salinity and freshwater budgets has been recognised by the SSIWG, and these complementary techniques have already been used around Antarctica in the detection and measurement of regional trends in freshwater flux. Secondly, both Level 2 and 3 data products undergo data filtering in pre-processing stages, and reject gridpoints that contain >50% sea ice presence, as well as data that is taken too close to land. The resultant averaging of gridpoints that have been rejected is particularly problematic for accurate representation of freshwater flux adjacent to the Antarctic coast and ice shelves. Thirdly, while the Level 3 data incurred significant data loss through averaging (with the Optimally Interpolated product available at a minimum 9-day average), the Level 2 OS data product required significant processing to 'stitch' together the individual half-orbit swath-based maps taken during the course of each day in order to produce a global map that could be reprojected to a polar stereographic image. It is recommended that future studies consider whether these limitations exist in other, similar datasets (such as the Aquarius mission), and whether lower-level data products of SMOS SSS measurements can be obtained to produce in-depth analysis of freshening and seasonal salinity trends around the Antarctic continent, adjacent to ice shelves, and around the edge of seasonal sea ice.

However, the monthly-average maps of SMOS Level 3 Optimally Interpolated data demonstrated a seasonal pattern that agrees with modelled predictions of freshwater flux in previous studies, which are linked to changes in oceanic circulation from growth and decay of seasonal Antarctic sea ice. This could indicate a role for remotely-sensed sea surface salinity (SSS) data in observing seasonal trends in surface freshwater flux, and could be a useful complement to direct measurements in detecting whether changes to freshwater flux in the Southern Ocean around the continent is a significant driver of increasing seasonal sea ice in Antarctica. It is vital that future studies closely examine and reduce the aforementioned data biases, as until these are minimised, it is unlikely that SSS data products, such as those from SMOS, can be utilised in detecting links between freshwater flux and seasonal sea ice extent.

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